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955 L'Enfant Plaza North, S.W.
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date: August 19, 1971

to: Distribution

B71 08029

from: C. Bendersky

subject: Rocketdyne and AiResearch Space Shuttle APU Studies Final Reviews - Case 237

ABSTRACT

The results of the two Auxiliary Power Unit (APU) system studies performed to support the Space Shuttle Technology Program are reported herein. The studies, conducted by both Rocketdyne and AiResearch, defined the characteristics of candidate gas turbine driven systems having a capacity of 400 shaft horsepower for electrical and hydraulic power. Preliminary designs were performed on systems which used gaseous H_2/O_2 combustion products.

The studies achieved their objective of providing design data to support the ongoing Space Shuttle study program.

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MEMORANDUM FOR FILE

1.0 INTRODUCTION

In support of the OMSF Space Shuttle technology requirements the Lewis Research Center has funded two study contracts in the auxiliary power unit (APU) areas. Both AiResearch and Rocketdyne were awarded identical 10-month studies having the objectives of (1) evaluating candidate APU configurations, (2) selecting and then executing a preliminary design analysis of the selected concept, and (3) recommending areas requiring technology efforts to ensure APU availability for the Space Shuttle program. A previous memorandum* described the results of the evaluation of the candidate APU configurations. This memorandum describes the results of the remainder of the studies as reported by the contractors at the Lewis Research Center on June 30 and July 1, 1971.

2.0 BACKGROUND

The Space Shuttle APU is a gas driven rotating machinery system that provides non-propulsive power for operation principally of electrical and hydraulic systems. APU's are not as efficient as fuel cells for producing electrical power. However, the Space Shuttle electrical power requirements are an order of magnitude larger than state-of-the-art fuel cells. On the other hand, APU state-of-the-art is well advanced and can provide a lightweight system which will satisfy this larger electrical power as well as the much larger hydraulic power requirements of

* AiResearch Space Shuttle APU System Study Review, Memorandum for File, Case 237, C. Bendersky, October 28, 1970.

the Space Shuttle. Based on the results of the evaluation of these candidate APU systems, NASA directed that the preliminary designs include the following ground rules:

1. APU propellants are to be H_2 and O_2 obtained as gases from accumulators which are part of the attitude control system (ACS).

2. The APU system must satisfy both orbiter and booster requirements. Each APU is to be a complete package, thermally insulated from the environment. A proper number of APU packages would be located in each stage to satisfy failure criteria.

Figure 1 displays a typical APU power flow while Table 1 lists selected APU operational parameters. NASA later directed both contractors to also study the effect of liquid H_2 and O_2 propellants because of interest shown in liquid propellants in the Space Shuttle Vehicle studies. At the completion of these studies it was intended to choose the best system concept and proceed into a breadboard technology program culminating in a system demonstration under simulated Space Shuttle conditions.

TABLE I

Power Output	
Peak, SHP	400
Idle, SHP	33
Hydraulic Cooling %	100
Propellant Supply (Gases)	
Hydrogen	
Temp., °R/Pressure, Psia	75-500/500-1000
Oxygen	
Temp., °R/Pressure, Psia	300-500/500-1000
Environment	
Pressure, Psia	0-14.7
Temp., °R	395-760 (Rocketdyne) 400-700 (AiResearch)
Typical Fluids	
Lube Oil	Mil-L-7808, 750°R (Max)
Hydraulic Oil	M2V, 530°R(Min), 750°R(Max)

3.0 DISCUSSION

3.1 AiResearch

3.1.1 Gaseous Propellant Systems

A schematic of the APU selected for preliminary design by AiResearch is shown in Figure 2. Turbine power is obtained from the combustion of fuel-rich mixtures of H_2 and O_2 and is transmitted to the hydraulic pumps and alternator through a gear train. Prior to combustion, the GH_2 is used to cool the gear lubricating oil and hydraulic fluid, recoup energy from the turbine exhaust gases and preheat the incoming accumulator supplied hydrogen.

The turbine is a 2-stage pressure compounded axial flow-type and operates at 70,000 rpm with 2060°R turbine inlet gas. Primary controls are the turbine interstage temperature, which is proportional to inlet temperature, and the turbine speed. The recouperator is designed to maintain the turbine exhaust gases above 700°R to prevent condensation or freezing of the water in the turbine exhaust gases. The conditioner has a hydrogen preheater and jet pump designed to mix both the cold side and hot side preheater flows. The jet pump discharge temperature is maintained above 400°R to prevent congealing or freezing the lube oil. Turbine power output is controlled by regulating the fuel and oxidizer flow to the combustor in a manner that will maintain a predetermined turbine interstage temperature.

The study effort included analysis of start up, shutdown and off-design conditions using analog and digital simulations. A fault detection analysis was performed and recommendations were made for secondary controls to effect emergency safe shutdowns. Since the control concept is compatible with that of the Space Shuttle vehicle, the controller can be remotely located from the APU.

Heated nitrogen gas may be used in place of the hot combustion gases for ground checkout. In this mode, the APU can provide 160 shaft HP at 40,000 rpm when supplied with GN_2 at 600 psia and 1200°R.

The chosen configuration meets the NASA study requirements with the following exceptions:

1. Hydraulic fluid temperature cannot be maintained lower than 750°R under all conditions as required. The APU can maintain the hydraulic fluid below 750°R at all conditions except prolonged operation at power levels below 80 shaft HP.

2. After shutdown, the final bearing temperature exceeds the NASA specified 290°F for the lube oil. However, the shutdown transient only effects a small portion of the APU life and is confined to an extremely small amount of oil. AiResearch reported operating various lubricants at temperatures up to 350°F for extended periods of time.

A weight breakdown and performance estimate for the AiResearch system is shown in Figure 3. For the specified orbiter* duty cycle the system weighed 463.3 lb of which 176.8 lb is fixed hardware.

3.1.2 <u>Liquid Propellant Systems</u>

AiResearch performed a cursory analysis of a liquid propellant fed APU. A schematic of the selected system is shown in Figure 4. Both H_2 and O_2 are stored as subcritical liquids. An electrically driven positive displacement pump was selected for LH_2 delivery and an electrically driven centrifugal pump was selected for the LO_2 delivery. Basically the APU is the same as the gas-fed version shown in Figure 1 with the following exceptions:

1. The gas generator used to power the turbine now operates with liquid rather than gaseous O_2.

2. The hydrogen conditioner jet pump flow control is no longer necessary as the LH_2 inlet temperature is no longer a variable.

Total weight and performance estimates for the system were not provided.

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* The orbiter performance will be used for comparisons because of its greater sensitivity with respect to payload than the booster.

3.2 Rocketdyne

3.2.1 Gaseous Propellant Systems

A schematic of the APU selected by Rocketdyne for preliminary design is shown in Figure 5. The system was based on a desire to regulate power output either by varying the turbine inlet pressure or by firing in pulses with only minor hardware and control differences between the two. Turbine power, as in the AiResearch system, is obtained from the combustion of fuel-rich mixtures of H_2 and O_2 and is geared to drive the hydraulic pumps and alternator. Prior to combustion, GH_2 is used to recoup energy from the turbine exhaust gases (regenerator), cool the hydraulic fluid, cool the lube oil and condition the GO_2 entering the combustor to approximately the same temperature as that of the GH_2. The combustor is designed to operate with GH_2 and GO_2 supplied at the same pressure and temperature. GH_2 flow bypasses are provided to prevent turbine exhaust gas condensation and maintain the hydraulic fluid and lube oil temperatures within operational limits.

The turbine is a 2-stage pressure compounded axial flow design, operates at 60,000 rpm and is designed for 2060°R inlet gas. Figure 6 presents the control system concept which was chosen for compatibility with either a pulse or pressure modulated power output mode. The primary controls are turbine inlet temperature and turbine speed. The turbine inlet temperature is not measured directly but is deduced from mixture ratio and combustion temperature and pressure. For pressure modulation, power output is varied by throttling the gas flow into the combustor at constant mixture ratio. During pulse modulation, the combustor is fired at a rate proportional to the power demand. Small gas accumulators located upstream of the combustor achieve the desired pulse response rate. For example, at an output of 33 HP at the gearbox, the pulse would be 0.102 seconds "on" 0.920 seconds "off." Start-up, shutdown, and off-design conditions were analyzed using analog and digital simulations. It is claimed that in both pulse and pressure modulated modes satisfactory startup can be achieved in

1.3 seconds and that full power can be delivered in less than 2 seconds. A failure mode analysis was performed in which logic was derived for fail-operational and safe-shutdown modes.

Rocketdyne stated that the APU can be adapted for use with an airbreathing turbine. Also it can be ground operated using 760°R, 500 psia GN_2 during which the output would be 120 shaft H.P.

The Rocketdyne baseline concept, however, does not comply with the study ground rule that the GH_2 propellant supply range between 250 and 350°R because this temperature is too high to maintain the hydraulic fluid below its maximum limit (750°R) in the orbiter duty cycle. Rocketdyne stated that to acceptably cool the hydraulic fluid, the GH_2 temperature entering the APU should be between 50 and 120°R. Several schemes were proposed to provide this lower temperature. The most simple (Figure 7) mixes LH_2 obtained directly from the ACS pumps with accumulator GH_2 to provide the desired APU inlet temperature. As stated in Figure 7, this results in a 30-50 percent weight increase over the baseline system.

Performance estimates for both pulse and pressure modulated systems are shown in Figure 8 as a function of pressure available in the ACS accumulators. The pulse control mode has a lower specific propellant consumption (SPC) and is relatively insensitive to supply pressure. Figure 9 presents total system weight for both pulse and pressure modulated baseline systems. The orbiter pulse modulated system total weight is 738 lb versus 828 lb for the pressure modulated system. The 90 lb weight saving of the pulse modulated version is achieved at the penalty of added complexity, particularly in the combustor ignition system, and potentially reduced system life due to the large cyclic thermal loads inherent with a pulsed system.

The previous weights include the propellant supply required by the ACS to deliver (condition) APU propellant to the ACS accumulators prior to use by the APU. This weight penalty was not included in the previously mentioned AiResearch system weights. On the same basis as the AiResearch weights, the pulse modulated orbiter APU weighed 539 lb which includes 233 lb of hardware and the pressure modulated APU weighed 586 lb which includes 214 lb of hardware.

3.2.2 Liquid Systems

Rocketdyne did not present any results of systems studies in which the APU was supplied both propellants as liquids. However, they did discuss systems in which the APU used pump-fed LH_2 from separate tankage and GO_2 supplied from the ACS accumulators. A hydraulic motor-driven positive displacement pump was chosen for LH_2 delivery. This cold H_2 delivery system solves the problem of supplying adquate hydraulic cooling capability for an orbiter duty cycle and purportedly can reduce the APU total system weight by 132 lb. No details of this system were presented.

3.3 Component Design and Technology

Both contractors presented a great deal of data on component design and state-of-the-art hardware. The turbomachinery, combustor, controls and off-design information were comparative and consistent. The data on heat exchangers were not. The AiResearch heat exchanger designs were described as extensions of existing production hardware designs. The Rocketdyne heat exchanger designs were based on analytical studies. The major APU technology areas flagged out by Rocketdyne are shown in Figure 10. AiResearch did not identify any key technology areas.

4.0 COMMENTARY

For the orbiter duty cycle, the AiResearch pressure modulated baseline system weighed 463.3 lb versus 536 lb for the pulse modulated and 586 lb for the Rocketdyne pressure modulated concepts. Thus the AiResearch system is 66 lb lighter (56 lb hardware) and 123 lb lighter (38 lb hardware) than Rocketdyne's. In addition, the Rocketdyne baseline concept does not meet the NASA requirements for cooling the hydraulic fluid without introducing additional system complexity and possibly additional weight. These considerations tend to favor the AiResearch concept. However, here are some additional subjective comments which reinforce the above.

The AiResearch system concept, without major change, is satisfactory for use with accumulator supplied gaseous propellants or liquid propellants supplied from separate tankage. The key to this capability (Figure 2) is the preheater/jet pump subsystem which prevents freezing of either the lube oil (400°R) or the hydraulic oil (530°R) using only a single recycle flow control loop. Use of liquid propellants require somewhat different component designs. With incoming subcritical LH_2, the preheater must vaporize as well as heat the H_2. Different configurations of heat exchangers are required for a LH_2 than for a GH_2 system. However, such heat exchangers are relatively easy to fabricate. Also, a combustor using LO_2 is more difficult to develop than one using GO_2. However, the present LO_2 burning gas-generator state-of-the-art should suffice for this component.

Rocketdyne did not describe an APU system using LH_2/LO_2 propellants. However, the baseline configuration (Figure 5) would probably require a different concept for hydraulic fluid temperature control as the problem of hydraulic oil freezing becomes more acute when LH_2 propellant is used. In addition, the turbine inlet temperature control system based on a constant GH_2/GO_2 mixture ratio would have to be changed due to the presence of LO_2.

C. Bendersky

1013-CB-ep C. Bendersky

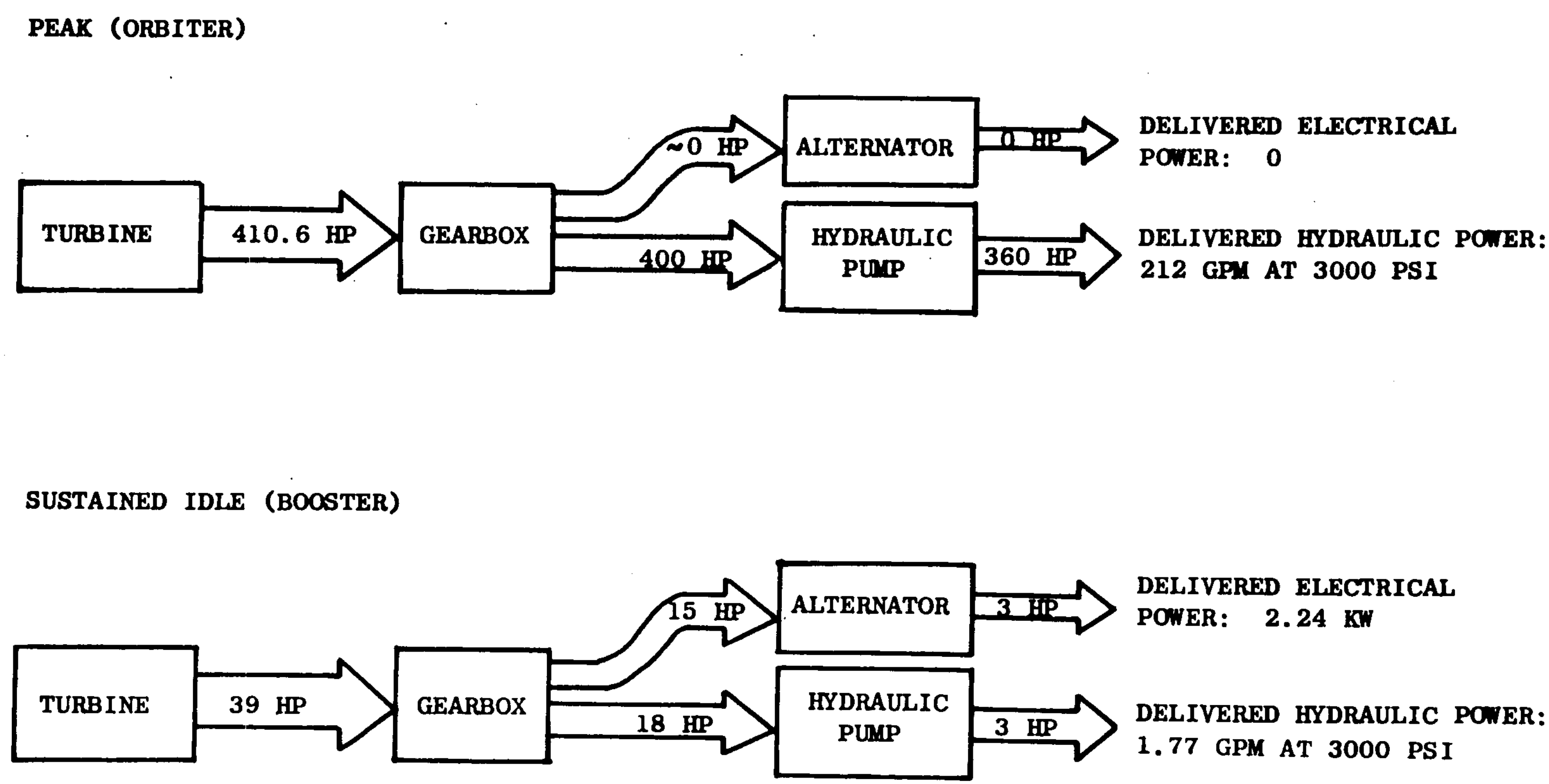


FIGURE 1 - TYPICAL APU POWER FLOW

SOURCE: ROCKETDYNE

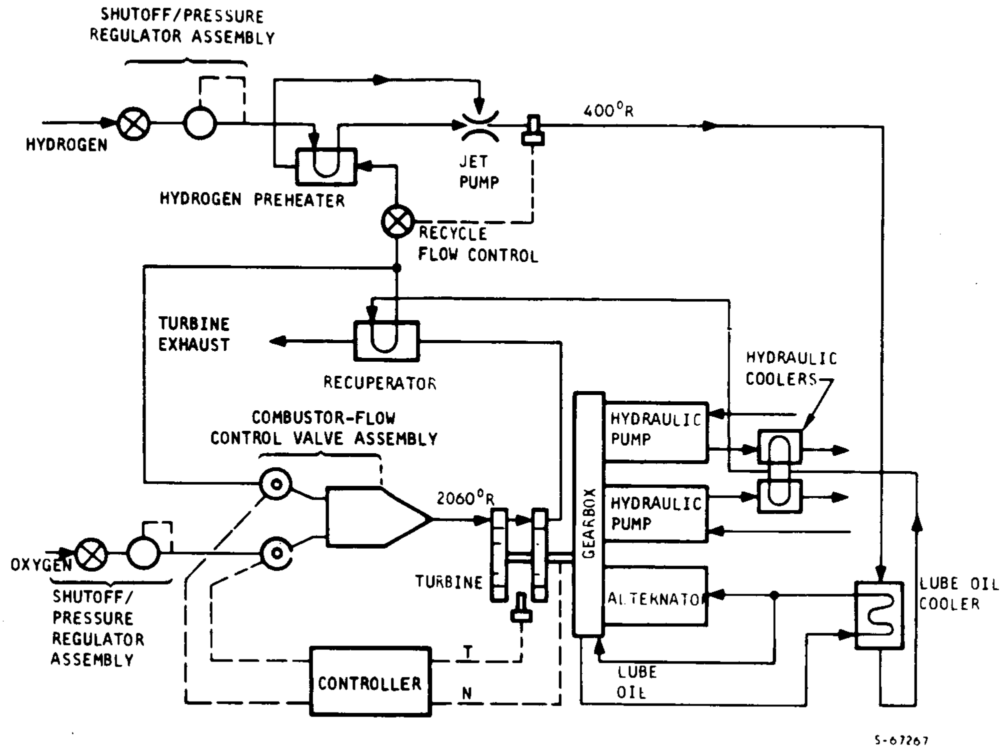


FIGURE 2 - SCHEMATIC OF AIRESEARCH BASELINE SYSTEM

SYSTEM PERFORMANCE

	Booster	Orbiter
Average SPC, lb/shp-hr	2.08	1.82
Average O/F	0.575	0.627
Total hydrogen-oxygen weight, lb	308.6	286.5

SPC = Specific Propellant Consumption

FIXED WEIGHT SUMMARY

Turbine-gearbox assembly	71.7 lb
Ducting	34.4
Lube and hydraulic coolers	31.6
Recuperator	11.8
Valving	8.6
Controls	7.0
Hydrogen preheater	6.1
Combustor/flow control assembly	5.6
Total fixed weight	176.8 lb

TOTAL SYSTEM WEIGHT

BOOSTER	ORBITER
485.4 lb	463.3 lb

FIGURE 3 - AIRESEARCH PERFORMANCE AND WEIGHT ESTIMATE FOR BASELINE APU SYSTEM

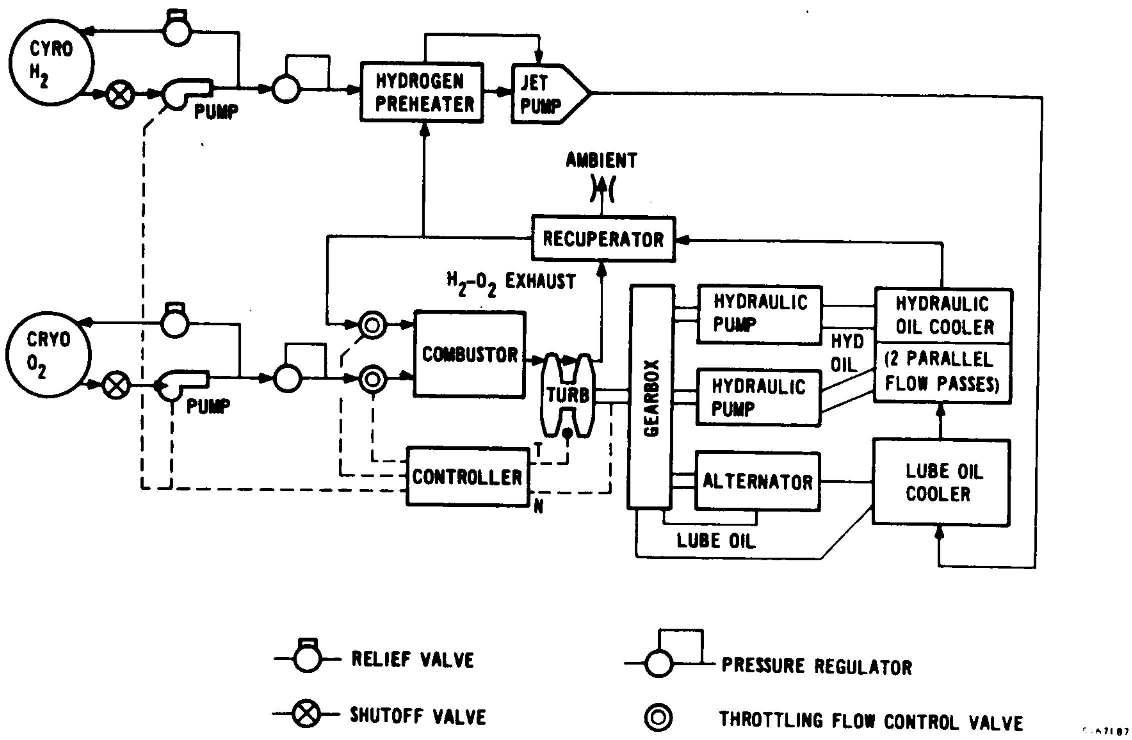


FIGURE 4 - AIRESEARCH LOW-PRESSURE CRYOGENIC LIQUID SUPPLIED SYSTEM SCHEMATIC

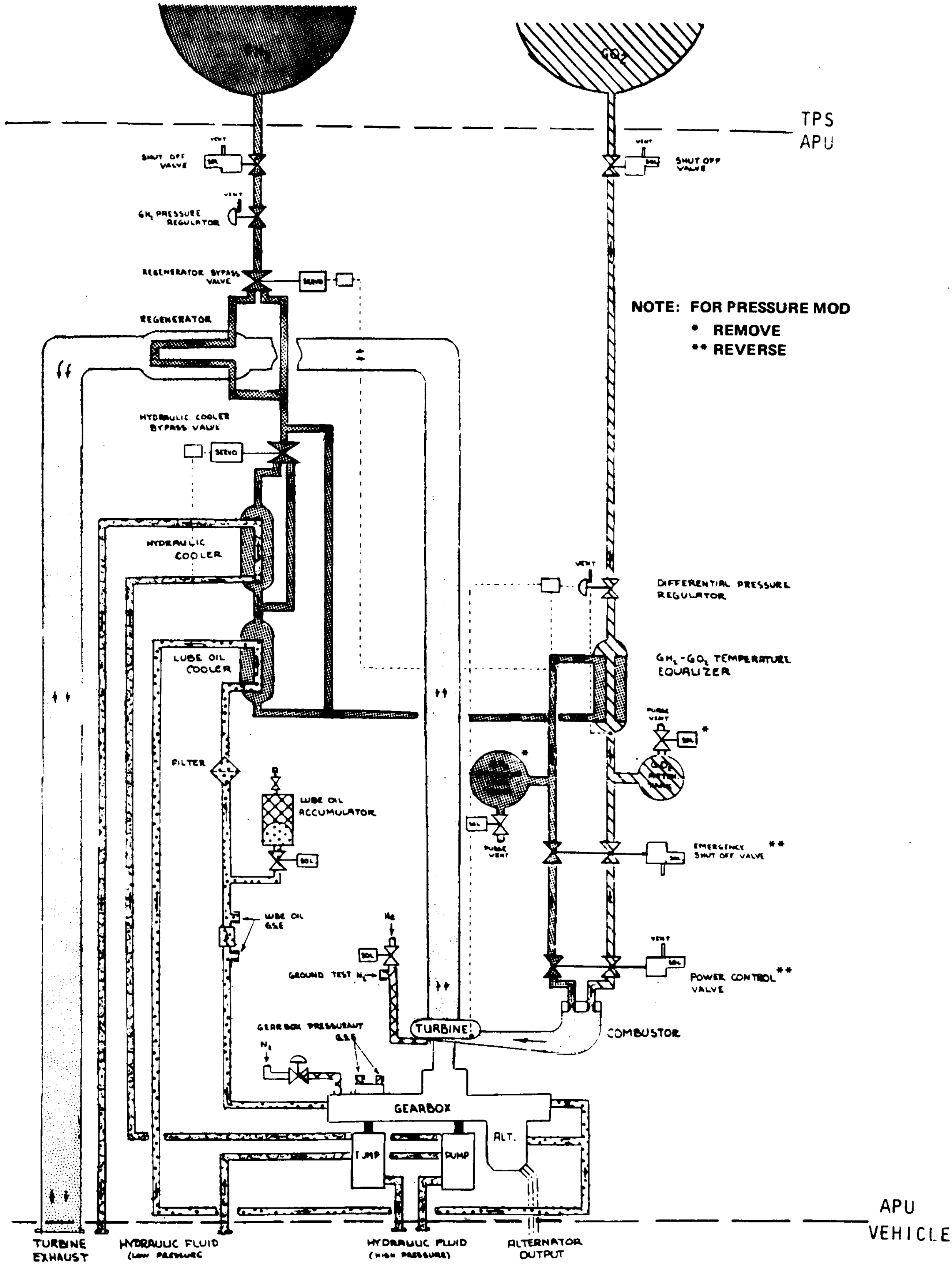


FIGURE 5 - ROCKETDYNE APU SYSTEM SCHEMATIC (PULSE MODULATED)

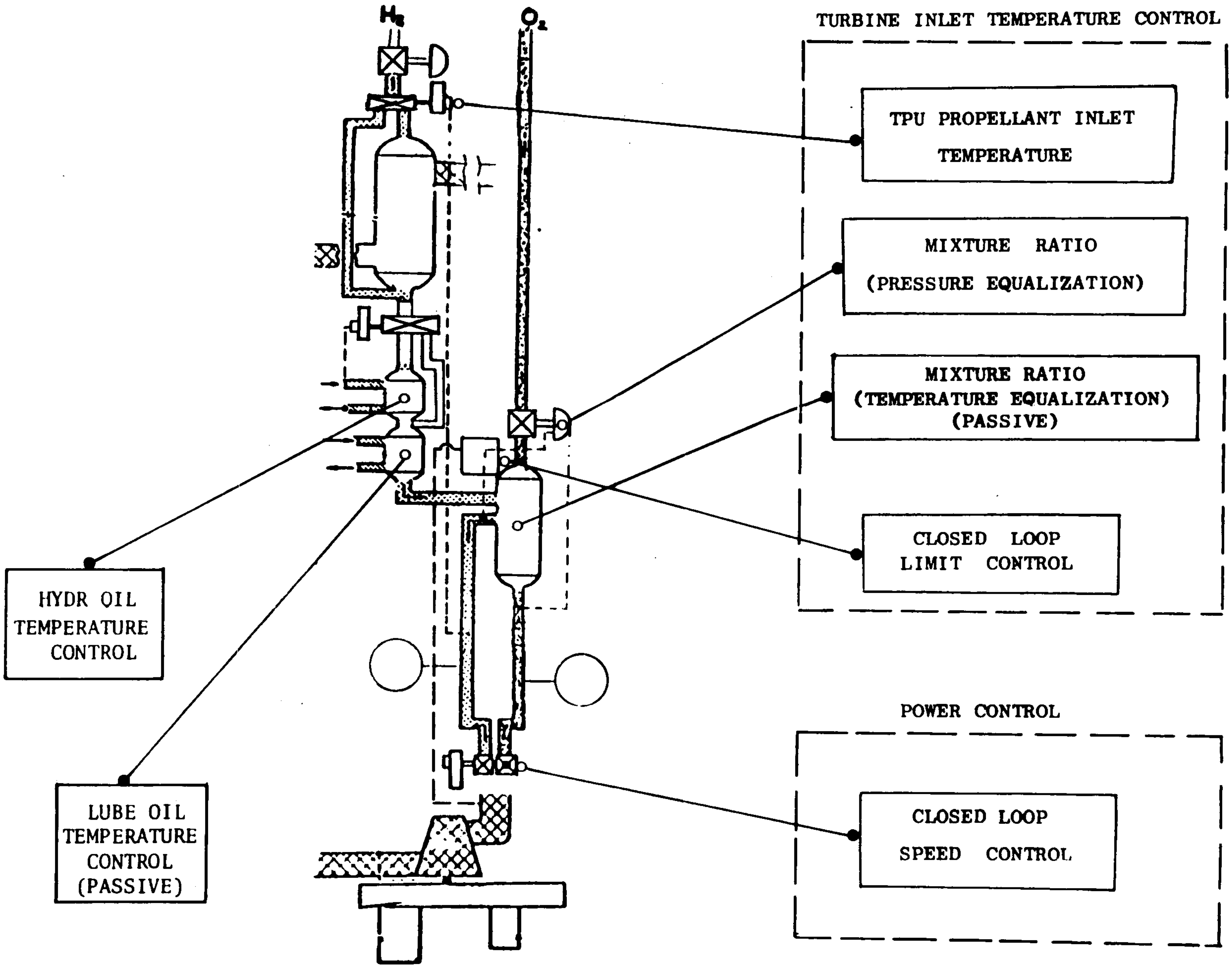
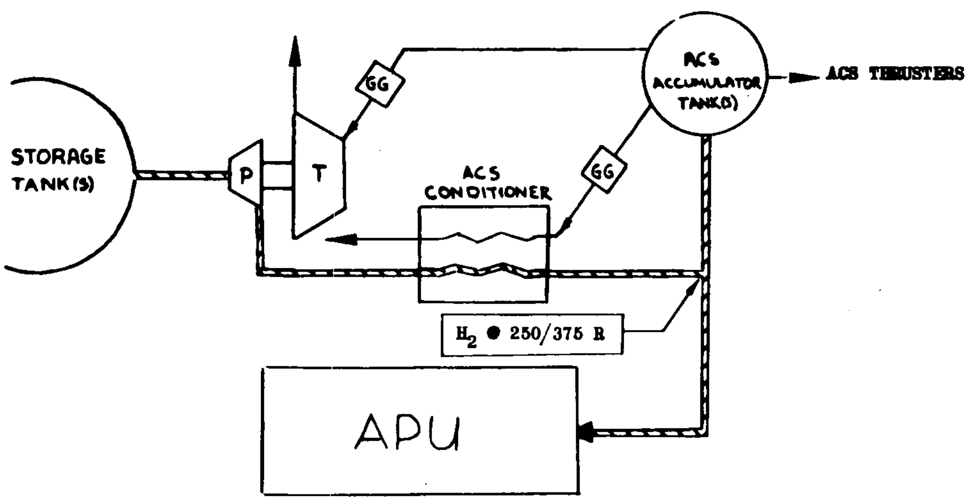


FIGURE 6 - ROCKETDYNE CONTROL SYSTEM PHILOSOPHY (PULSE & PRESSURE MODULATED SYSTEMS)

INTEGRATED ACS PROPELLANT FEED SYSTEM



- 50-125 R H_2

  REQUIRED FOR ORBITER

  HYDRAULIC COOLING

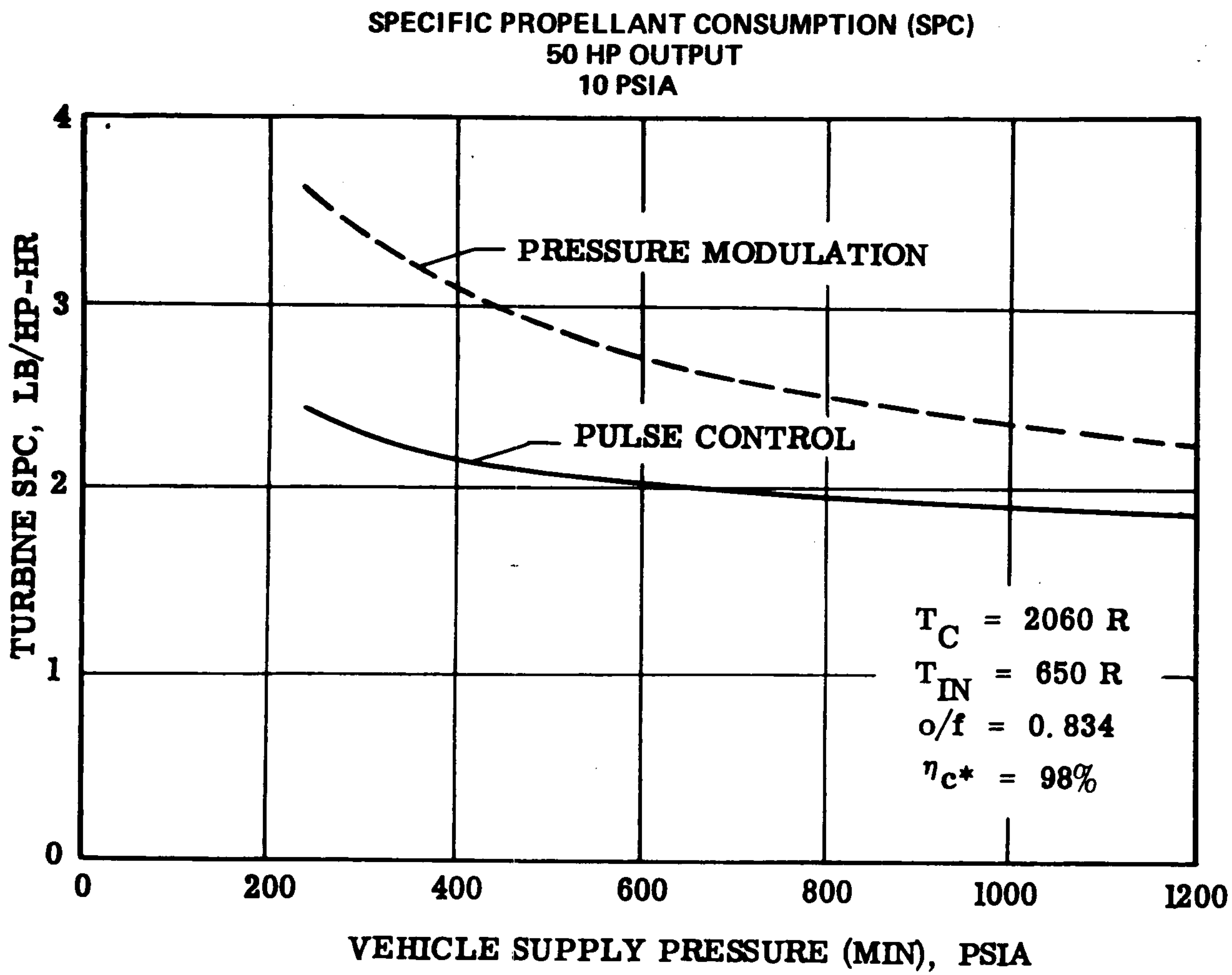
- PROPELLANT CONDITIONING PENALTY

  30-50%

  FOR ACS INTEGRATION*

*ACS = ATTITUDE CONTROL SYSTEM

FIGURE 7 - ROCKETDYNE VEHICLE/ACS/APU INTEGRATION LIMITATIONS



BURNED PROPELLANT LB PER APU

SUPPLY PRESSURE (PSIA)	500		1150	
MAXIMUM TURBINE INLET (PSIA)	390		900	
	B	O	B	O
PRESSURE MODULATION	468	372	348	318
PULSE CONTROL	322	306	306	290
ΔW	146	66	42	28

FIGURE 8 - ROCKETDYNE APU EFFECT OF VEHICLE SUPPLY PRESSURE ON PERFORMANCE

COMPONENT	SYSTEM			
	PULSE MODULATED		PRESSURE MODULATED	
TURBOPOWER UNIT				
• TURBINE AND GEARBOX ASSEMBLY	55		55	
• GAS GENERATOR AND CONTROL VALVE	10		12	
• CONTAINMENT	15		15	
PROPELLANT CONDITIONING				
• PRESSURE REGULATORS (2)	16		16	
• BYPASS VALVES (2)	17		17	
• REGENERATOR	26		26	
• HYDRAULIC COOLER	10		10	
• LUBE OIL COOLER	8		8	
• TEMPERATURE EQUALIZER	1		1	
• ATTENUATION TANKS	17		0	
LINES, DUCTS, VALVES, L.O. ACCUMULATOR	24		21	
INSTRUMENTATION/CONTROLS	12		12	
STRUCTURAL SUPPORTS	23		21	
APU HARDWARE WEIGHT	233		214	
	BOOSTER	ORBITER	BOOSTER	ORBITER
BURNED PROPELLANT	322	306	468	372
PROPELLANT SUPPLY PENALTY (INTEGRATED ACS)	153	199	222	242
TOTAL	708	738	904	828

FIGURE 9 - ROCKETDYNE APU — SYSTEM WEIGHT SUMMARY (BASE LINE)

TURBO POWER UNIT

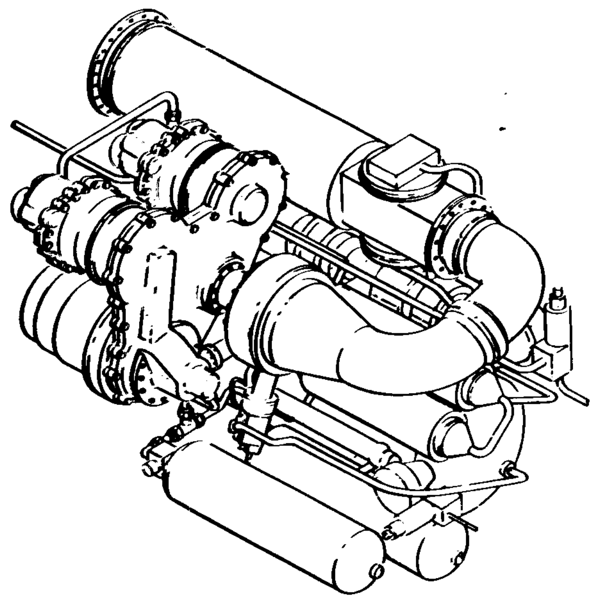
COMBUSTOR – IGNITION

COMBUSTION
(PRESS MOD)

TURBINE – STAGE TRANSITION

OFF DESIGN
(PRESS MOD)

H_2 EMBRITTLEMENT



PROPELLANT CONDITIONING

HEAT EXCHANGER – FREEZING

SAFETY

PROPELLANT CONTROL

TURBINE INLET TEMP CONTROL

POWER CONTROL

VALVE LIFE –
(PULSE CONTROL)

FIGURE 10 - ROCKETDYNE APU MAJOR TECHNOLOGY AREAS

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